

Cosmological puzzle resolved by stellar feedback in high redshift galaxies

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The standard cosmological model, now strongly constrained by direct observation at early epochs, is very successful in describing the structure of the evolved universe on large and intermediate scales¹. Unfortunately, serious contradictions remain on smaller, galactic scales^{1,2}. Among the major small-scale problems is a significant and persistent discrepancy between observations of nearby galaxies, which imply that galactic dark matter (DM) haloes have a density profile with a flat core³⁻⁶, and the cosmological model, which predicts that the haloes should have divergent density (a cusp) at the centre^{7,8}. Here we use numerical N-body simulations to show that random bulk motions of gas in small primordial galaxies, of the magnitude expected in these systems, result in a flattening of the central DM cusp on short timescales (of order 10^8 years). Gas bulk motions in early galaxies are driven by supernova explosions which result from ongoing star formation. Our mechanism is general and would have operated in all star-forming galaxies at redshifts $z \gtrsim 10$. Once removed, the cusp cannot be reintroduced during the subsequent mergers involved in the build-up of larger galaxies^{9,10}. As a consequence, in the present universe both small and large galaxies would have flat DM core density profiles, in agreement with observations.

It is now widely accepted that structure in the universe formed hierarchically, with small DM haloes forming first, later merging to make increasingly large virialized objects¹. Analysis of cosmological simulations showed that DM haloes form with a central density cusp, with the innermost logarithmic slope being close to -1 (refs. 7, 8). This is in sharp contrast to observations which imply that galactic DM haloes have a flat central core³⁻⁶.

The proposed solutions to the problem of cosmological cusps can be broadly divided into three categories: (1) observational problems, (2) new physics (beyond standard cold DM, hereafter CDM, cosmology) and (3) conventional mechanisms (within the standard CDM cosmology). The observational solutions appear to be ruled out by the newest results which suggest that neither limited angular resolution⁴ nor non-circular gas motions⁵ can be responsible for the flatness of the inferred galactic central density profiles. Among the new physics approaches, the warm DM scenario is problematic because the first galaxies capable of reionizing the universe appear to form too late to explain the early reionization observed by the Wilkinson Microwave Anisotropy Probe¹¹. Another modification of standard CDM, self-interacting DM, cannot simultaneously explain the very small cores observed in clusters of galaxies and the large cores observed in small galaxies¹².

All conventional solutions within the standard CDM model rely on some source of gravitational heating of the DM to flatten the cusps. It has been suggested, for example, that a DM cusp can be erased by a central bar¹³, by passive gravitational evolution of self-gravitating gas clouds orbiting near the centre of the galaxy¹⁴, by recoiling black holes¹⁵, or when a powerful starburst drives all of the gas out of the galaxy¹⁶ (“maximum feedback”). These mechanisms are not believed to be sufficiently efficient or general and are not widely accepted as resolving the discrepancy².

We propose an efficient new mechanism for flattening the central DM cusp that is driven by the random bulk gas motions that are expected to be present in all star-forming primordial galaxies. Random bulk gas motions on scales of a few hundred parsecs are seen in all nearby large^{17,18} and small¹⁹⁻²¹ galaxies for which good quality radio observations are available and are a predicted result of stellar feedback²²⁻²⁴ (from the combined action of stellar winds and supernovae). In both

observations and numerical simulations, the typical random velocities of the gas clouds are close to or slightly above the sound speed in interstellar gas, or $\sim 10 \text{ km s}^{-1}$ (refs 17–24); clouds moving with highly supersonic speeds quickly lose kinetic energy via radiative shocks. Significantly, the spatial scale of the bulk gas motions is comparable to the scaling radius of high redshift ($z \gtrsim 10$) galaxies and the gas clouds’ velocities are close to their typical DM particle velocities. The result of the bulk gas motions is that the central gravitational potential of the galaxy fluctuates on a timescale comparable to the crossing time for DM particles creating an efficient channel for transferring kinetic energy from gas to DM. The process is reminiscent of the violent relaxation that takes place in collapsing self-gravitating N-body systems²⁵. That this effect has not been observed in numerical simulations to date is a result of the formidable computational challenge of simulating a realistic interstellar medium (ISM), subject to stellar feedback, inside a live DM dwarf galaxy halo.

Our model is fundamentally different than those relying on passive gravitational evolution of gas clumps in that it identifies a physically plausible source of energy to force hydrodynamic motion for long time periods. It is instructive to compare our model with that of El Zant *et al.*¹⁴ in which the source of energy used to heat the DM is the orbital energy of massive, self-gravitating gas clouds, moving in the dense central part of the galaxy. This model correctly identifies moving massive clumps as the key mechanism able to transfer kinetic energy from gas to DM, but provides no mechanism to maintain these clouds or their kinetic energy on the timescales necessary to achieve cusp flattening. Indeed, such clouds would form stars and fragment due to stellar feedback on a timescale of $\sim 10^7$ years and, further, the supersonically moving clouds would slow down and fragment due to the interaction with the surrounding inter-cloud medium on a comparable timescale. These timescales are much shorter than those required to flatten the cusp, $> 10^8$ years. As a result, *the energy of the orbital motion of gas clouds is not available for flattening the cusp*. We propose instead that the natural source of energy for erasing the cusp is the energy of the stellar feedback. This energy is used to maintain the interstellar gas in the required clumpy state and to drive the gas clouds to sonic speeds over long intervals of time ($> 10^8$ years); both effects are necessary if the cusp is to be removed.

To understand the essence of our mechanism, consider the central part of a DM halo with characteristic radius, R , and velocity dispersion, σ . If stellar feedback drives a significant fraction of the gas, of mass m , to one side of the system then the potential will fluctuate by an amount $\sim Gm/R$ (G is Newton’s constant). During one crossing time, $\sim R/\sigma$, DM particles can gain or lose kinetic energy of up to this amount depending on whether they are falling towards the gas concentration or moving away from it. If the random bulk velocity of the gas V is comparable to σ , subsequent motion of the gas concentration will reinforce a net increase in velocity dispersion, σ , and a secular transfer of kinetic energy to the DM. The effect is expected to be sensitive to the velocity dispersion of the gas bulk motions and the mass of the gas involved, but not to the density of the gas concentration. If the gas bulk motions are much faster than the velocity dispersion of DM particles ($V \gg \sigma$), the effect becomes negligible as the particles do not have time to react to changes in the potential and move instead in response to the time-averaged gas density distribution. In the opposite limit, with $V \ll \sigma$, the potential fluctuates slowly enough that the whole system can readjust adiabatically, again resulting in negligible energy transfer.

To estimate the importance of our mechanism in cosmological haloes, we ran a set of numerical simulations motivated by observational cues from nearby galaxies and that were designed to provide tractable physical models. Our model for the large-scale bulk gas motions in these systems places most of the gas in three large clumps moving as harmonic oscillators through the centre of the galaxy along three orthogonal axes, with phases shifted by $2\pi/3$ (see Table 1). This model both provides the required imposed hydrodynamic forcing as well as permitting direct control over key parameters.

Figure 1 shows the evolution of the initial Navarro-Frenk-White⁷ (NFW) density profile due

Table 1: Model parameters

Parameter	Value
Halo virial mass, m_{vir}	$10^9 M_{\odot}$
Halo virial radius, r_{vir}	3 kpc
Halo scaling radius, r_s	0.85 kpc
Halo scaling density, ρ_s	$0.16 M_{\odot} \text{pc}^{-3}$
Gas mass, m	$(0.25, 0.5, 1) \times 10^8 M_{\odot}$
Radius of the gas clumps, h	40, 200 pc
Amplitude of the oscillations, A	400, 850 pc
Mean gas speed, V	$4 - 63 \text{ km s}^{-1}$
Number of DM particles, N	$32^3, 64^3, 128^3$

The fiducial model corresponds to $m = 10^8 M_{\odot}$, $h = 40 \text{ pc}$ and $A = 400 \text{ pc}$.

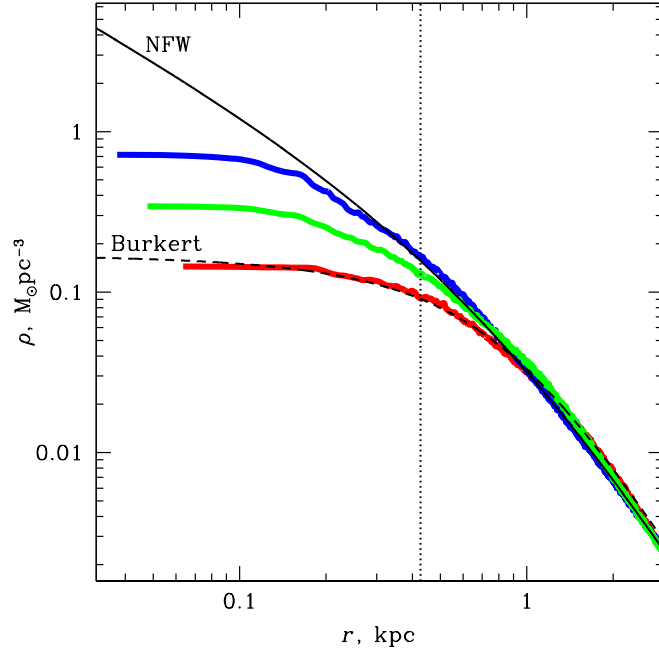


Figure 1: Evolution of the DM density profile in the fiducial model. The mean bulk gas speed is $V = 11 \text{ km s}^{-1}$ and the number of DM particles is $N = 128^3$. The solid black line corresponds to the initial NFW profile, the dashed black line shows the corresponding Burkert³ profile. The blue, green, and red lines show the density profiles of the simulated halo after 40, 80, and 140 Myr, respectively. The vertical dotted line marks the radius $A = 400 \text{ pc}$ (the amplitude of the oscillations).

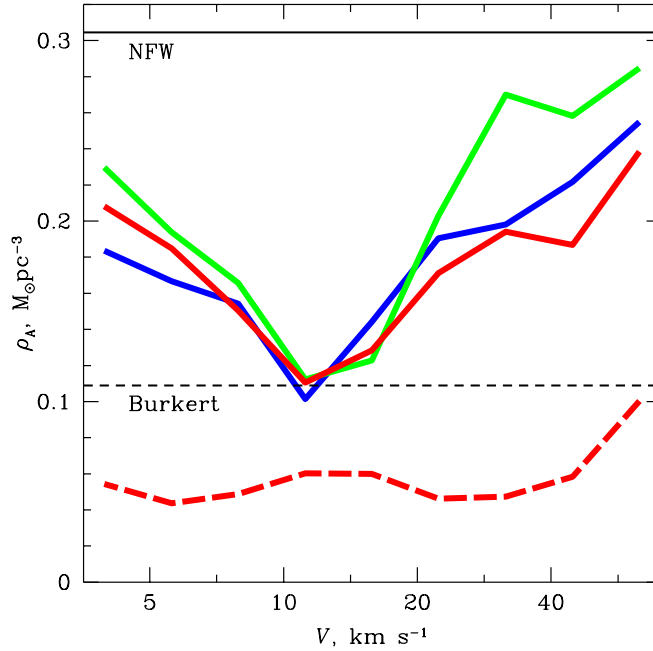


Figure 2: Degree of flattening of the central DM cusp for different models. The averaged (within radius $A = 400$ pc) central DM density ρ_A is plotted as a function of the mean bulk gas speed V . The black solid and dashed lines correspond to NFW and Burkert profiles respectively. Red lines correspond to our fiducial model at $t = 140$ Myr (solid) and $t = 600$ Myr (dashed). The green line corresponds to the model with a more than hundred times lower gas density ($h = A/2 \simeq 200$ pc) at $t = 220$ Myr. The blue line corresponds to the model with a twice smaller total gas mass at $t = 240$ Myr.

to the model gas bulk motions (with $V = 11 \text{ km s}^{-1}$) and shows that flattening of the central density cusp is effective on a timescale as short as 140 Myr, *just one full period of the gas clump oscillation*. At $t = 140$ Myr, the DM density profile of the evolved halo is in remarkable agreement with observed (Burkert³) profiles. Thus the mechanism can operate on a timescale during which active stellar feedback would be expected in dwarf galaxies and on a sufficiently short timescale that the cusp flattening would be complete before the dwarf is involved in a significant merger in the structure formation hierarchy.

We tested the robustness and sensitivity of this result using several other parameter choices bracketing our fiducial model. Figure 2 shows the dependence of the cusp flattening on the mean speed, V , of bulk gas motions as well as on the gas mass and density. As expected, the most efficient transfer of kinetic energy from gas to DM occurs for gas velocities comparable to the velocities of DM particles: for our fiducial model, after ~ 200 Myr of evolution, the effect is strongest (with the central DM density becoming comparable to that observed) for $V = 10 \dots 20 \text{ km s}^{-1}$. These velocities are in the same range as the observed velocity dispersions of interstellar gas bulk motions. After $\gtrsim 500$ Myr of evolution, a very significant cusp flattening is achieved for a much wider range of \tilde{V} (see Fig. 2). (Further simulations are described in Methods.)

We conclude that the observed properties of interstellar random bulk gas motions — a spatial scale of a few hundred parsecs and mildly supersonic — are just right to lead to fast erasure of the central DM cusp in small primordial galaxies. For very small galaxies ($< 10^7 M_\odot$), the

impact of stellar feedback is so strong that the whole ISM is driven out at supersonic speeds via galactic winds²⁶. For much larger galaxies ($> 10^{10} M_{\odot}$) stellar feedback plays a minor role, as the gravitational potential is deep enough to retain the ISM²⁶, and the rotational speed of the disk is much larger than the speed of the random bulk gas motions. Our mechanism, in which stellar feedback drives most of the ISM in bulk motions which are confined within the DM halo, is hence expected to operate efficiently in a wide range of primordial galaxies whose masses lie somewhere between 10^7 and $10^{10} M_{\odot}$. During subsequent evolution, a fraction of the galactic gas will be consumed by star formation and lost via galactic winds, leaving a gas content in agreement with observations of present-day dwarf galaxies. As these galaxies merge together to make larger ones, the flat-cored shape of the DM density profile is preserved^{9,10}. As a result, in the modern universe most galaxies with masses $\gtrsim 10^8 M_{\odot}$ should have central DM densities smaller than the predictions of pure DM cosmological models — in agreement with observations.

A fully self-consistent demonstration of the effects described in this paper requires the inclusion in simulations of detailed physical models of both star formation and feedback in high redshift galaxies. Ultimately, the goal is to follow at high resolution the hierarchical assembly of dwarf galaxy DM haloes in the full cosmological context together with the evolution of their gaseous and stellar contents.

It is noteworthy that if, indeed, most star-forming galaxies in the early universe lost their DM cusps because of stellar feedback, another persistent cosmological problem could also be solved. The essence of this problem is that the standard cosmological model predicts that a large galaxy such as our own should have 10 to 100 times more small satellite galaxies than is observed²⁷. Dwarf galaxies without a central cusp have a lower average core density than cuspy ones, and are hence much easier to disrupt tidally during the hierarchical assembly of larger galaxies²⁸. As a consequence, the removal of galactic cusps by stellar feedback in the early universe would result in fewer satellites today.

Methods

We generated equilibrium DM haloes corresponding to a typical early universe galaxy (see Table 1) with the NFW⁷ density profile. The three gas clumps are represented by rigid spherical bodies with characteristic radius, h , mass, m , and softened gravitational acceleration $g(r) = -Gm/(r^2 + h^2)$. The spatial amplitude of the oscillations, A , was chosen to be $r_s/2 \simeq 400$ pc. All three bodies have the same mean speed, V , which is a free parameter. The gravitational N-body code GADGET²⁹ was used to evolve the models.

In our fiducial model, the total masses of gas and DM enclosed within the radius A are both equal to $10^8 M_{\odot}$. As the universal baryon to DM density ratio is $\sim 1/5$ (ref. 11), this gas mass corresponds to $\sim 1/2$ of all gas in the galaxy. The radius, h , of the gas clumps is 40 pc. We explored a range of V from 4 to 63 km s⁻¹, corresponding to $(1/8 \dots 2)V_c$, where $V_c = 32$ km s⁻¹ is the circular velocity of the DM halo at $r = A$. The accuracy of the simulations was such that the total energy was conserved to better than 0.02% (for a DM only model).

We tested our fiducial model with $V = 11$ km s⁻¹ with three different resolutions ($N = 32^3$, 64^3 , and 128^3), and found the resulting DM density profiles of the evolved haloes to be identical within measurement errors. We also re-simulated this model with much higher accuracy (with the resulting average time step being a factor of 7 shorter), and again found the results to be virtually identical to the original run.

We also checked if the initial adiabatic compression of the central part of the DM halo due to the presence of the gas would affect our results. Placing all of the gas ($10^8 M_{\odot}$) in our fiducial model within the central 200 pc resulted in the central DM density slope becoming slightly steeper

(logarithmic slope -1.4 instead of -1) after ~ 100 Myr of evolution (no gas bulk motions were allowed). We then evolved this adiabatically compressed halo in the presence of bulk gas motions with parameters identical to our fiducial model with $V = 11 \text{ km s}^{-1}$. After ~ 50 Myr of evolution, the DM density profile became identical to that of the original run within the measurement errors.

A model with half the gas mass (corresponding to the averaged gas density within $r = A$ being $1/2$ that of the DM) still shows a very strong effect, with the time required to achieve complete cusp flattening being 240 Myr (see Fig. 2). Only when the averaged gas density drops to $1/4$ that of the DM does the effect become significantly weaker, with a cusp flattening time of ~ 800 Myr (not shown).

In agreement with the discussion above, the strength of the effect does not depend significantly on the density of the gas clumps. In Figure 2 we show the results for a model with $h = A/2 \simeq 200 \text{ pc}$, with the gas clump density being more than hundred times lower than in the fiducial case. In this model the Burkert-like central DM density is achieved after 220 Myr.

The level of gas compression, required by our model, is not unreasonable, as cosmological simulations of dwarf galaxy formation show comparable or even larger central gas concentrations prior to the first starburst³⁰. It is also consistent with the analytical prediction (which follows from the conservation of angular momentum) that the size of the galactic gaseous disc should be $\sim \lambda r_{\text{vir}}$, where $\lambda \simeq 0.05$ is the dimensionless angular momentum of cosmological haloes. Nevertheless, we tested the case of much lower gas concentration by running our model with the amplitude of oscillations, A , being twice larger ($A = 0.85 \text{ kpc}$), for the lower gas density case ($h \simeq 200 \text{ pc}$). In this run, the time required to flatten the cusp becomes approximately twice longer (460 Myr), which is still smaller than the local Hubble age at $z = 10$, $t_{\text{H}} = 490 \text{ Myr}$. Interestingly, this time is again of the order of the oscillation period.

We also tested the effect of more than 3 gas clumps. For $\gtrsim 10$ clumps we observed the central DM cusp becoming even more pronounced than initially (due to adiabatic compression). This suggests that small-scale turbulence (with spatial scale $\ll r_s$) cannot erase the central DM cusp.

The energy requirements for driving the bulk gas motions in our fiducial model with $V = 11 \text{ km s}^{-1}$ are quite modest. Ignoring energy input from stellar winds and assuming that each supernova releases 10^{51} ergs of thermal energy, we find a required supernova rate of $8/\xi \text{ Myr}^{-1}$, where ξ is the fraction of supernova energy transformed into kinetic energy of the bulk gas motions. Assuming a Salpeter stellar initial mass function and $\xi = 0.1$, this corresponds to a modest star formation rate of $0.01 \text{ M}_{\odot} \text{ yr}^{-1}$. The corresponding gas depletion timescale is $\sim 10 \text{ Gyr}$, which is comparable to the values for the observed dwarf irregular galaxies.

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